Chapter 20
Biorefining: A Green Tribological Perspective

P. L. de Vaal, L. F. Barker, E. du Plessis and D. Crous

Abstract As a developing country, South Africa is in a unique position with regard to establishing, maintaining and expanding infrastructure to ensure compliance with international trends with respect to *environmental regulations*, while at the same time establishing the means to provide access to affordable energy to all its citizens to share the potential of its resources. In many respects, tribology plays an important role in saving of energy as well as ensuring that requirements with regard to protecting the environment are complied with. Green tribology can rightly be regarded as an approach which is timely and which has an impact on many activities like electricity generation, production of synthetic fuels and lubricants, mining operations and protection of the environment and its resources. Focusing on the interface between Tribology and *Biorefining*, several interesting possibilities open up. With the constant rise in the price of oil, alternatives to crude oil as primary energy source and as basic feedstock for fuels and chemicals are becoming more and more attainable. In this chapter an overview is provided of the above, from a South African perspective. A number of case-study

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M. Nosonovsky and B. Bhushan (eds.), *Green Tribology*,
Green Energy and Technology, DOI: 10.1007/978-3-642-23681-5_20,
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examples are given which indicate that a "green" approach in finding engineering solutions to tribological problems which could have a far-reaching impact on the environment. Three examples are used, namely how proper selection of tailor-made *lubricants* could decrease *energy usage* in gear-driven systems. The focus here is on the power industry, where coal-based power plants are the only economically feasible solution to the increasing demand for electricity in a developing economy with virtually no crude oil reserves. The success atttained in this endeavour should stimulate similar projects in the mining sector of the country. In the second instance, ingenious application of tribology with respect to application of specialised lubricants from a renewable source, namely plant oils, can decrease cost of lubrication and, in addition, can resolve difficult issues with regard to disposal of contaminated waste in *metal cutting* operations, indicating the value of a "green tribology approach". Thirdly, combining the concept of biorefineries, tribology and the ability to synthesise products to suit specific requirements, including formulation of lubricants and fuels, can lead to substantially improved products, impacting in a positive way on the environment.

20.1 Introduction

South Africa's economy is heavily dependent on coal. According to the World Energy Council (WEC) South African coal resources were estimated to be approximately 34 billion short tons at the end of 2007, accounting for 95% of African coal reserves and 4% of world reserves. Coal provided an estimated 72% share of the country's total primary energy supply in 2007 and accounts for approximately 85% of electricity generation capacity. Coal is also a major feedstock for the country's synthetic fuel industry.

It is understandable that coal should and will play a significant role in the South African industry. In addition, South Africa's petrochemical industry is largely based on conversion of coal to chemicals, via Sasol's *Fischer–Tropsch* process, which makes it unique in the world.

In 2008, South Africa produced 195,000 barrels per day (bbl/d) of oil, of which about 160,000 bbl/d was synthetic liquids processed from coal and natural gas. South African oil consumption is estimated to be 575,000 bbl/d, of which, approximately 380,000 bbl/d is imported (67% of consumption). South Africa has a highly developed synthetic fuels (synfuel) industry, creating liquid fuels from coal and natural gas. State company PetroSA and petrochemicals giant Sasol are the major players. PetroSA manages the world's largest commercial natural gas-to-liquids plant at Mossel Bay in the Western Cape, with a capacity of 45,000 bbl/d. Sasol, an oil, gas and chemical company, operates the world's only commercial coal-to-liquids synthetic fuels facility. According to the Department of Minerals and Energy, approximately 36% of liquid fuel demand in South Africa is met by synthetic fuels.

The concept of biorefining has been tested and tried in many ways—one of the main reasons holding back full exploitation of the concept is the economical feasibility of such processing when it has to compete with processes using crude oil. From an environmental perspective, the concept of a biorefinery satisfies many of the potential problems posed by conventional refineries—providing a means to convert renewable resources into chemicals of a widely-varying nature and only limited by the ingenious application of technology.

With rapidly dwindling resources of crude oil, utilising renewable feedstocks forms the key to the successful application of biorefining: If renewable feedstocks could be used, many of the problems related to diminishing resources would be solved. It is however important to relate the scale of petroleum- or coal-based refineries to the current potential of refineries using renewable feedstocks. Initially only in special cases, based on the market-demand for specialised chemicals, would a venture in this direction be economically feasible.

Processing alternatives are largely determined by technical and by economical viabiliity. It is always interesting to focus on benefits of existing technology, and how that can be extended or enhanced by new technology.

In the case of Sasol's *coal-to-lquid (CTL)* FT-based operations in South Africa, one of the benefits of producing liquid products starting from synthesis gas, is that there is potentially more control over the process of synthesising chemical compounds.

In addition, *gas-to-liquid (GTL)-technology*, also making use of the FT-process, enables the same benefit, which leads to production of petrol, diesel, jet fuel as well as polyalphaolefins, the base material for the production of a variety of lubricants.

Due to South Africa's unique position with regard to generation of electricity via primarily coal and due to current difficulties of generating sufficient electricity, many production plants in the country, now focus strongly on utilisation of excess, or unused energy sources, which are available in a variety of forms, depending on the type of operation, e.g. paper and pulp, smelters in the minerals processing industry, the agricultural sector, etc.

The term "green fuels" can be interpreted in a variety of ways: In the first instance it could point towards the origin of the fuels, i.e. not based on depletable resources, like crude oil, but rather based on a renewable resource, of an origin which could include a variety of vegetable oils, including rapeseed, soybean, sunflower seed, castor oil etc., but also several other possibilities, including sugar cane, cellulose and cellulose waste and a variety of algae, and then applying any of several processing routes, including fermentation, gasification and further modification into virtually any hydrocarbon-based commodity for which the demand can be identified.

An alternative interpretation of green fuels could be to focus on the effect that the products of combustion may have on the environment. To this end, several exciting possibilities are under investigation.

Current *fuel specifications* were developed around crude-oil-based products and engine technology of a bygone era. It took many years to ensure that well-controlled product ranges can be produced internationally with reasonable comfort and ease.

With stricter demands being placed on the effect that fuels and combustion gases have on the environment, several properties of fuels and lubricants need to be determined based on their desired behaviour in a much more demanding environment. This is in a process of giving rise to a brand new set of required product specifications.

With regard to fuel, South Africa has a lot of experience in the production of synthetic fuels via the Sasol-route. In the case of diesel fuel, the Sasol fuels are essentially sulphur-free. The lubricity of coal-derived diesel has to be improved by suitable additives. Active research in this field is ongoing locally. Successful development of synthetic jet fuel is another achievement of late.

Supplementing diesel by biodiesel, a renewable resource which is known to have good lubricity properties is an alternative approach that has to be investigated. Contrary to the approach taken in other parts of the world, considerable attention has to be given to the idea of using a feedstock that could have been used for human consumption, like maize and sunflower, which are the two crops cultivated locally with the best potential given the climatic conditions before this is converted and added to supplement fuel supplies.

20.2 Green Tribology with Applications to Biorefineries

Biorefining is the concept of processing renewable biomass feedstock into chemical products and energy. Unlike current commercial bioprocesses that mainly focus on producing a single product and treating everything else obtained as a by-product, in a biorefinery all the available feedstock should be utilised, gaining as much value out of it as possible. The *biorefinery* concept is very much like a modern day fossil fuel refinery, producing a broad range of products while using as much of the feedstock as possible. The main difference is however the fact that the feedstock of a biorefinery would be a renewable resource, while the products would be hydrocarbon-based, similar to a conventional crude-oil-based refinery [1].

The Sasol Coal-to-Liquid (CTL) plants in South Africa use the Fisher-Tropsch (FT) route to produce liquid hydrocarbons. To this end, *fuels*, namely gasoline, diesel and jet fuel (aviation turbine fuel) are produced, complying with international specifications, but with the added advantage that some of these products have improved performance characteristics, reducing the unwanted compounds in exhaust gases. Also, the potential of synthesising liquid lubricants via selective manufacturing, enables prodution of synthetic lubricants, which have tailor-made properties.

Biorefining as a concept is not new and references to this date back to the nineteenth century. As an example the German chemist, Mitscherlich, reported in 1878 how sugar, a waste product of the sulphite pulping process, can be fermented and how glue can be made from the waste liquor of a pulping plant [1]. The reason

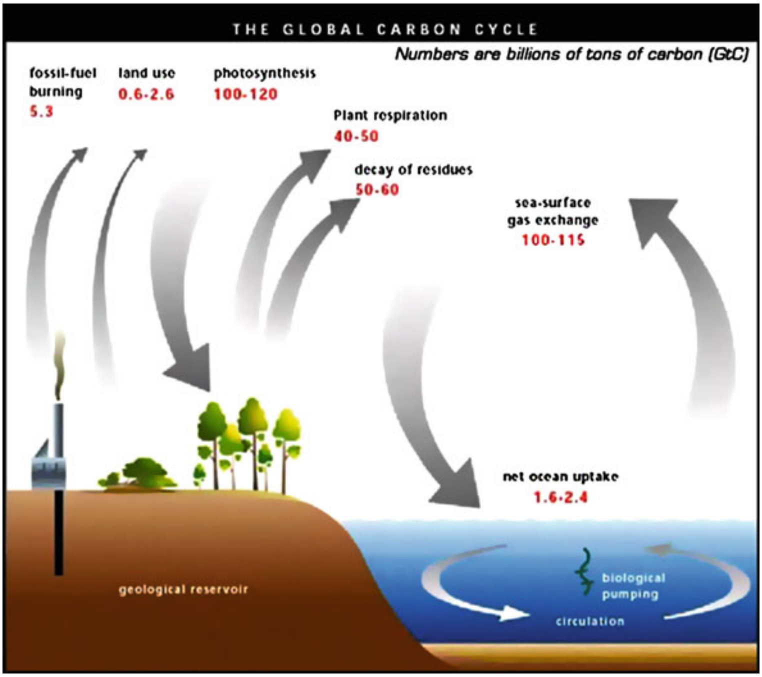


Fig. 20.1 Representation of the carbon cycle [4]

so much attention has turned to it lately is because of increasing environmental awareness and the realisation that fossil fuel supplies will run out.

When the word biorefining is heard, the product most commonly thought of is *biofuels*. The largest current producer of bio-ethanol is Brazil, producing a total of 27.5 billion litres of bio-ethanol during the 2008/2009 harvests [2]. The bio-ethanol is used extensively in their local industries, as a transport fuel and is exported around the world. The acceptance of ethanol as a transport fuel in Brazil has been extremely successful to the point where some manufacturers have made engines specifically for use with the ethanol blends available in Brazil. The total number of “flex-fuel” cars sold in 2008 accounted for 91% of all car sales in Brazil during 2008 [3].

While the use of fossil fuels creates an increase of carbon in the world’s carbon cycle (Fig. 20.1) biorefining has the potential of being carbon neutral. Their products can also have direct green house gas emission reduction effects, as in the case of bio-ethanol where it has been shown that using ethanol in transport fuels reduce carbon emissions, even when used in a mixture (mixed with fossil fuels), by as much as 19% [3]. Bio-degradable bio-plastics, another potential product, have the obvious benefit to reduce plastic wastes. Some plants might be used to directly reduce CO_2 emissions, as in the case of algae which use photosynthesis to turn CO_2, sunlight and water into usable products. Current “wastes” that are rich in carbon and biomass all have the possibility of becoming feedstock, furthering the contribution of biorefineries.

20.2.1 Classification

According to Van Ree and Annevelink [5], the current bio-based industries (maize mills, pulp– and ethanol plants) are not seen as complete biorefineries. Even so they are a good starting point for further development as they use methods for separating and processing *biomass* similar to the ones expected to be used in new biorefineries but still require more complete use of their feed materials and side streams. Some of these current day industries are so similar to the expected biorefinery concept that research has been done to upgrade them to biorefineries by adding some additional processes that makes further use of their side streams, for instance heat and *power generation* using the lignin by-products [6, 7]. Currently the most advanced commercially operating biorefinery is owned and operated by Borregaard in Norway [8]. It uses lingo-cellulosic feedstock (wood) to create speciality cellulose, lignin, vanillin (by modifying lignin) and sugars.

The classification of biorefineries depends on their preferred feedstock and the main process routes involved. These classifications are as follows:

- Two platform biorefineries
- Lingo-cellulosic biorefineries
- Whole crop biorefineries
- Green biorefineries
- Aquatic/Marine biorefineries
- Thermo-chemical biorefineries

20.2.1.1 Two Platform Biorefinery

The "two platform" biorefinery can accommodate essentially any biomass type with high carbohydrate content. In this concept the feedstock is separated into a sugar platform chemical and the residues thereof (Fig. 20.2). This is obtained through enzymatic–, acid– or catalytic hydrolysis to saccharify the biomass.

The sugar side of the biorefinery has an immense range of possible products with varied options of processes that can be used to get to those products. Screening of the products showed that the best candidates are high-value products, as mass produced, low-value commodity products have low production costs using conventional production processes.

For the syngas platform the best products (short term) are hydrogen and methanol as production of alcohols, aldehydes, mixed alcohols and *Fischer–Tropsch* products are not competitive with their fossil fuel derived counterparts

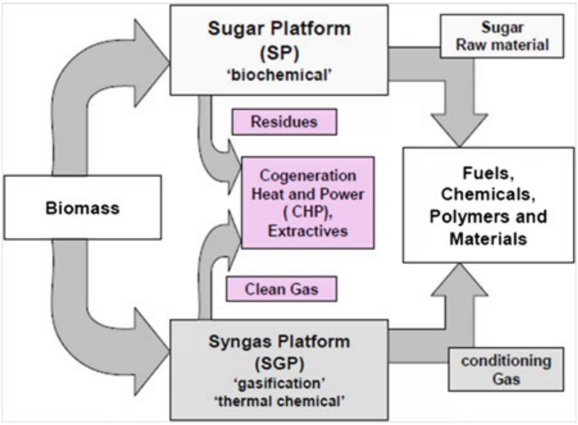


Fig. 20.2 Two-platform biorefinery [1]

at the current oil price [9]. Compared with coal, to create the same amount of fuel from wood would require almost 4 times the weight in wood at best, taking into account that natural wood is almost 50% (w/w) water and has a carbon content of around 48% [10], while coal has 80–99%. For fermentation only 20% of oven dried wood is usable carbon that can be turned into ethanol fuel [11].

20.2.1.2 Ligno-Cellulosic Feedstock Biorefinery

Ligno-cellulosic feedstock (LCF) biorefineries are good candidates for being one of the most promising types of biorefineries because of their favourable feedstock materials and product possibilities [1]. Their feedstock can be any kind of plant based biomass, from forestry and papermaking waste to agricultural waste like maize stover and straw. The reason for the LCF's wide range of feedstock usage is that it separates the feedstock into its main components namely cellulose, hemi-cellulose and lignin (Fig. 20.3). This allows for specialised reactions tailored to each of the components that can then produce a range of products from innovative bio-based chemicals to even traditional *petrochemical* based products.

While the array of products that can be produced is extensive, the state of lignin processing as of 2007 is not very efficient with respect to effective usage of lignin [12] as lignin is mostly used "as is" for fuel or as a binding agent in various applications. Processing of lignin could yield a lot of high-value aromatics that could significantly boost the profitability of its use in a biorefinery but the techniques to do so still need considerable development.

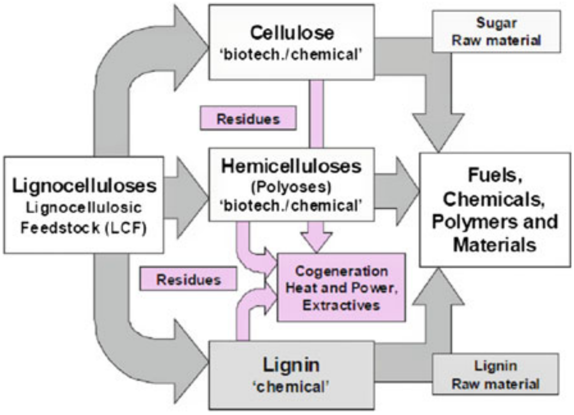


Fig. 20.3 Ligno-cellulosic feedstock biorefinery [1]

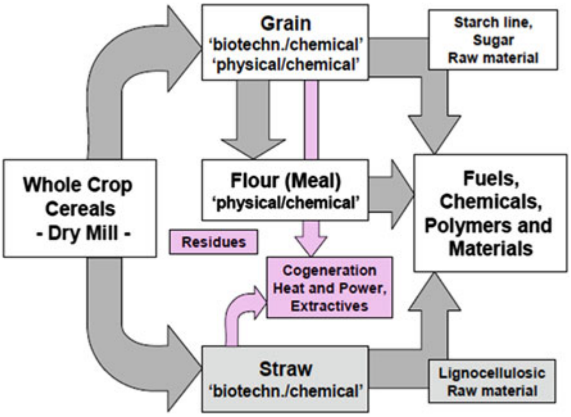


Fig. 20.4 Whole crop biorefinery overview (dry milling) [1]

20.2.1.3 Whole Crop Biorefinery

As the name suggests a whole crop biorefinery uses an entire harvested crop (rye, wheat or maize) along with all parts that would typically be seen as waste. For this reason the most common first step is to separate the "waste" straw (leaves, nodes, ears and chaff) from the grains (90:10 weight ratio, respectively) mechanically by dry milling it [1]. Each of the components can then be processed in a different platform (Fig. 20.4).

The straw side can be separated in the same way as with an LCF *biorefinery* and processed accordingly. Another option for the straw is to convert it to syngas using pyrolysis. The grain can be processed to a variety of products.

An alternative to dry milling is wet milling, where the grain is swelled and pressed to release high-value oils (Fig. 20.5). The advantage of wet milling is that the production of the natural structures (starch, cellulose, oil and protein) are kept high while the resulting processes used are common [1]. The products produced

Fig. 20.5 Whole crop biorefinery (wet milling) [1]

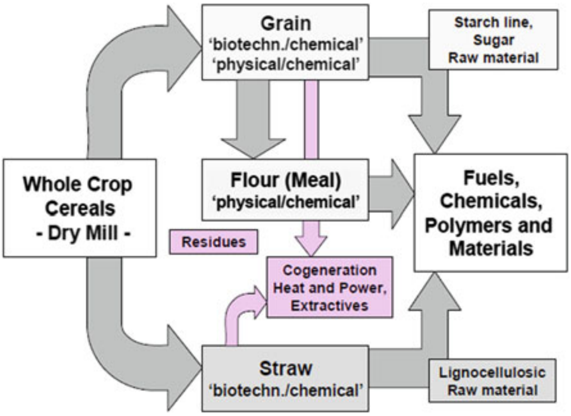
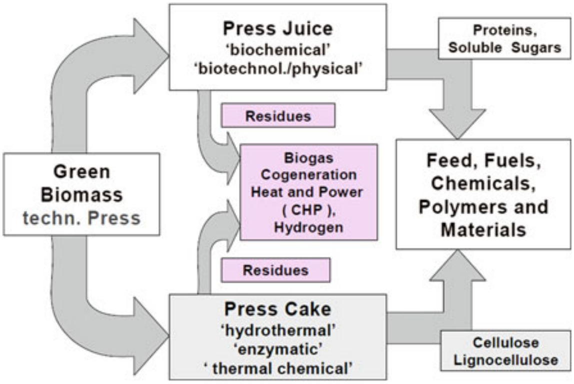

Grain
'biotechn./chemical'
'physical/chemical'
Starch line, Sugar Raw material
Whole Crop Cereals - Dry Mill -
Flour (Meal)
'physical/chemical'
Fuels, Chemicals, Polymers and Materials
Residues
Cogeneration Heat and Power, Extractives
Straw
'biotechn./chemical'
Lignocellulosic Raw material

Fig. 20.6 Green biorefinery [1]



from wet milling are some high-value pharmaceutical cosmetic chemicals though the feedstock costs are quite high when compared to others. A major advantage is that this technology has been in use with maize as a feedstock since 1992 yielding primarily fuel alcohol, high-fructose syrup, starch and dextrose, amongst other products.

20.2.1.4 Green Biorefinery

A green biorefinery uses "green" biomass (grasses, lucerne, clover and immature cereals) in a process called green fractionation to produce two main platforms, a press juice platform containing mostly liquids and a press cake platform with the remaining solids (Fig. 20.6) [1]. Green fractionation is wet fractionation of green biomass and allows for the co-production of food and non-food products, a great benefit considering that a lot of the biomass used in various biorefineries could cut into their use as a food resource. The scalability of a green biorefinery is also a big advantage, capable of processing from a few tons per hour to 100 tons per hour of *green biomass*. Rapid production or preservation methods will have to be used with the primary products and the feedstock both of which various preservation methods have various effects on the composition of the materials.

Numerous products can be obtained from either the press juice, also green juice, or the press cake. The press juice contains large quantities of proteins, lactic acid, vitamins, and dyes that can be separated out and processed further. The press cake mainly contains crude drugs, pigments and other organic compounds that are commonly pressed into pellets for various uses but containing high amounts of cellulose and lignin that can be processed further, however it is not as accessible as that found in a LCF biorefinery [1].

20.2.1.5 Aquatic/Marine Biorefinery

Aquatic/marine biorefineries (AMB) use either macro-algae (*seaweeds*) or micro-algae (diatoms, green- and golden *algae* as well as blue-green algae, cyanobacteria) either as a feedstock and/or for the processing of CO_2. The CO_2 reduction potential of micro-algae has been known for some time and seaweeds have been exploited commercially with 8 Mt of wet biomass being produced in 2003. Products from seaweeds include food, feed, chemicals, cosmetic- and pharmaceutical products mainly produced in Asian countries. On average, seaweeds are more proficient at converting solar energy to biomass than land-based plants owing to their simpler cellular structure and easier access to CO_2, sunlight and nutrients given the optimum conditions. Algae also have the benefit of increasing a country's biomass supply without the need to clear land. [13].

Current uses of micro-algae are focused around supplemental and feed uses. Proposed micro-algae biorefineries fall in two main categories, in the one the algae are harvested and used as a biomass source (similar to what is currently done) while another option is to use modified algae that produce a specific product like ethanol that does not need harvesting. Algae can be grown in open pond systems or in enclosed photobioreactors that are either transparent or use light fibres or tubes to carry sunlight to the algae. It has also been suggested to use heterotrophic algae, which use the carbon as an energy source as well as a carbon source, in conventional fermentors. On the one side open pond systems are very cheap while the photobioreactors require a higher capital cost, however, the photobioreactors are much smaller, eliminate contamination and allow for precise control over conditions meaning better efficiencies.

Production of *bio-diesel* from micro-algae has been investigated but it was found that competing prices from other bio-diesel sources were just too low (less than €1/kg) [13]. It has also been shown using the best assumed growth rates, most favourable selling prices and the most optimistic green house abatement that it will still be infeasible to produce only fuels from the micro-algae though this could change with increased fossil fuel prices.

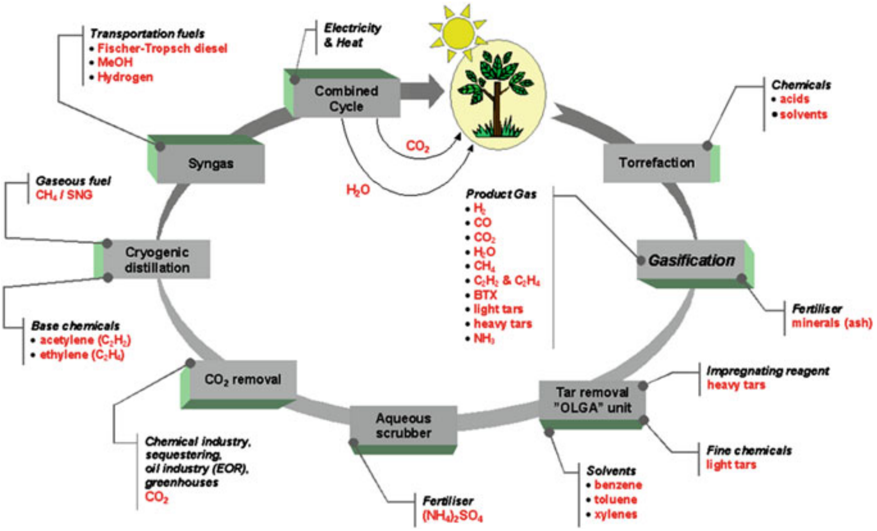


Fig. 20.7 Thermo-chemical biorefinery [5]

Other proposed uses for aquatic biomass include electricity generation through co-firing, biomethane production through fermentation and liquid fuel generation through pyrolysis (bio-oil). But producing algae solely for these purposes would still not make it economically viable. More promise has been shown in its ability to capture CO_2, possibly directly from the exhausts of industries and power plants, however screening is required for algae that can handle high CO_2 saturation levels. In the same way algae can be used to process waste water, removing excess nutrients, xenobiotics and heavy metals. High-value products that can be obtained from algae include methane, iodine, algin, mannitol, polymers, high-value oils, colourants, nanomaterials, new pharmaceuticals and cosmetics [13].

20.2.1.6 Thermo-Chemical Biorefinery

A thermo-chemical biorefinery (TCB) relies on a series of different processes such as pyrolysis, torrefaction (a milder pyrolysis performed on biomass) and gasification to process biomass into different products (Fig. 20.7). Even though all these processes work on more or less the same principles (elevated temperatures and pressure) each produces a different range of the products that can be taken off between the processes (Fig. 20.8) in what is also called the staged catalytic biorefinery.

An alternative option to having a TCB as a stand alone biorefinery is to incorporate it into a current petrochemical plant by using any biomass or biomass derived intermediates in the proposed TCB processes to supplement the use of petrochemical feedstock. Referred to as “green upgrading” this could be the first commercial use of the TCB [5].

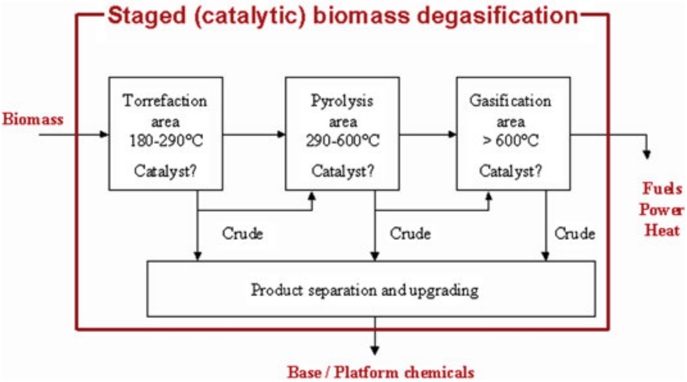

Staged (catalytic) biomass degasification
Biomass
Torrefaction area 180-290°C Catalyst?
Pyrolysis area 290-600°C Catalyst?
Gasification area > 600°C Catalyst?
Crude
Crude
Crude
Product separation and upgrading
Fuels
Power
Heat
Base / Platform chemicals

Fig. 20.8 Staged catalytic biorefinery [5]

20.2.2 Processes and Products

An overview of the different categories of *biorefineries* with respect to the feed materials, processes and status is given in Table 20.1. Once the feedstock has been fractioned into their platform chemicals/materials they are ready for further processing. The most common non-mechanical types of processes that are used can be categorised as biochemical or thermo-chemical processes.

The biochemical processes are a collection of processes derived from natural processes using enzymes, bacteria and yeasts. The possible products from biochemical processes are enormous and are mostly products from sugars, with the prime example being ethanol production. There are other high-value products as well, such as xylitol and furfural. Xylitol is a sugar alcohol made from the sugar xylose, which can only be found in plants, that has commercial application as a non-nutritive sweetener. Furfural is a sugar derived building block with a growing market where a wide range of new uses are being investigated [9].

Thermo-chemical processes, as the name suggests, require elevated temperatures and so more energy. The products from these processes are very much like those obtained from petrochemical feed-stocks such as fuels. Thermo-chemical processes include pyrolysis (no air), gasification (partial air), liquefaction (no air, high pressure), Fischer–Tropsch and combustion (excess air).

Depending on the residence time and temperature, *pyrolysis* can produce charcoal, char, bio-oil, chemicals and gas. The bio-oils obtained from pyrolysis are made up of a mixture of water, guaiacols, catecols, syringols, vanallins, furancaboxaldehydes, isoeugenol, pyrones, acetic acid, formic acid, other carboxylic acids, sugars and phenolics [14].

Gasification is similar to pyrolysis except that some oxygen and air is added to allow for partial oxidation of the products. Apart from chemical products the gas from *gasification* is an efficient source to generate electricity from, either by producing steam or directly in a gas turbine or engine, the alternative being

Table 20.1 Overview of biorefinery platforms [5]

Concept	Type of feedstock	Predominant technology	Development phase
Green Biorefineries (GBR)	wt biomass: green grasses and green crops, such as lucerne and clover	Pretreatment, pressing, fractionation, separation, digestion	Pilot plant (and R&D)
WholeCrop Biorefineries (WCBR)	whole crop (including straw) cereals such as rye, wheat and maize	Dry or wet milling, biochemical conversion	Pilot plant (and Demo)
Ligno-Cellulosic Feedstock Biorefineries (LCFBR)	Lingo-cellulosic-rich biomass: e.g. straw, chaff, reed, miscanthus, wood	Pretreatment, chemical and enzymatic hydrolysis, fermentation, separation	R&D/Pilot plant (EC), Demo (US)
Two Platform Concept Biorefineries (TPCBR)	All types of biomass	Combination of sugar platform (biochemical conversion) and syngas platform (thermo-chemical conversion)	Pilot plant
Thermo-chemical Biorefineries (TCB	All types of biomass	Thermo-chemical conversion: torrefaction, pyrolysis, gasification, HTU, product separation, catalytic synthesis	Pilot plant (R&D and Demo)
Marine Biorefineries (MBR)	Aquatic biomass: micro algae and macro-algae (seaweed)	Cell disruption, product extraction and separation	R&D (and Pilot plant)

combustion of the biomass to produce steam. Synthetic gas (syngas), a mixture of hydrogen and carbon monoxide, is a very flexible platform chemical. Depending on the ratio of these and sometimes the addition of water many different hydrocarbons (liquids, gases and solids (waxes) can be produced. The *Fischer–Tropsch* process uses syngas to produce a wide range of products, all of which are currently produced in the petrochemical industry.

20.2.3 Biomass

Feedstock to a biorefinery should be sustainable (renewable) meaning that unlike fossil fuels there should not come a time when it inevitably runs out. For this reason the prime feedstock for biorefineries is plant material. This biomass can be harvested or collected and then regrown, converting CO_2 in the air into sugars, oils and other useful chemicals, thereby staying carbon "neutral". Most of the suggested feed-stocks are already being used in various processes, e.g. woody biomass for pulp manufacture, sugarcane and maize for ethanol production and algae for their various uses. The leap to second and third-generation *biorefineries* (Table 20.2) will be to fully utilise the non-food feedstock potential and fine tune the processes involved. A third-generation demonstration biorefinery has been

Table 20.2 Classification of biorefineries based on their generation technologies showing their feedstocks and products [14]

Generation	Feedstocks	Examples
First-generation	Sugar, Starch, vegetable oils or animal fats	Bioalcohols, vegetable oil, biodiesel, biosyngas, biogas
Second-generation	Non-food crops, wheat straw, maize, wood, solid waste and energy crop	Bioalcohols, bio-oil, bio-DMF, biohydrogen, bio-Fishcer-Tropsch diesel
Third-generation	Algea	Vegetable oil, biodiesel
Fourth-generation	Vegetable oil, biodiesel	Biogasoline

commissioned but large integrated third-generation biorefineries are not expected to become established until 2020 [14].

Apart from water, the main components of plant matter are cellulose, hemicellulose, starches, sugars, lignin and extractives. These components are present in all plant biomass and vary in composition depending on the exact plant, which is the reason for all the different types of biorefineries.

Hemicellulose and *cellulose* are sugar polymers that make up the cell walls of plants. Cellulose has a rigid, crystalline structure made of β bonded (1–4) glucose molecules in a straight chain that is extremely resistant to hydrolysis. Hemicellulose, a branched polymer, is made up of different sugar monomers, among them are xylose (predominantly), galactose, mannose and arabinose. While not as strong as cellulose, hemicellulose is easier to hydrolyse and has a wider range of sugars to offer.

Lignin is a complex polymer with no set structure or pattern that provides bonding between different layers in a plant. It is made up of various aromatics which, if they can be hydrolysed without being destroyed could be valuable products. The technologies required to do so are still not fully developed and requires considerable research before they could be used in industry. Lignin as a whole is currently used as a bonding agent, compressed into pellets as an energy source, or directly burned to provide heat and power.

Extractives generally make up a small part of a plant and consist of fats, waxes, resins, photosterols and non-volatile hydrocarbons [Paperonweb]. Because they make up such a small part of the overall biomass they are largely ignored.

20.2.4 Biorefining in South Africa

Biorefining was first investigated in South Africa as early as 1970 by the CSIR when alternate sources of petroleum-based fuels were of great interest [15], but was abandoned after 1994 as an active area of research. With recent growing international focus on biorefining and utilization of biomass research in this field has seen a steady growth in South Africa.

As far as biomass production goes South Africa is in a very good position to be a competitor in *biorefining* with its range of climates for diverse agriculture and its established forestry industries. In 2005 South Africa was ranked 9th in the world for its maize (primary source of bio-ethanol production in the USA) production and 12th for its sugarcane (primary source of bio-ethanol in Brazil) production [16].

The forestry industry in South Africa is well established since the government started a plantation after World War 1 and the expansion by the two leading paper manufacturers (Sappi and Mondi) [17] in 1980. Currently South Africa has 1,2 million hectares of timber plantation producing a total of 18,5 million tons of wood used in a variety of industries, but primarily the production of paper and pulp, which has a lot of similarities with biorefining and would find adaptation to the biorefining industry fairly easy with their current operations in the biomass processing field.

While both the agricultural and forestry industries are very good sources for biorefineries South Africa also has a few non-conventional sources for biomass. One of these is the “Working for Water” incentive, started in 2005, where alien plant material is removed to increase water flow throughout the country. It has been estimated that the plant material removed up to date under this incentive could supply the entire paper and pulp industry for a year (almost 11 million tons) and could be used as an alternative biomass source for biorefineries, at least until the “Working for Water” incentive comes to an end [18].

The South African plants developed by Sasol utilising Fischer–Tropsch technology (High-Temperature Fischer–Tropsch, or HTFT), produce a product spectrum of products, including gasoline, diesel and aviation *fuel*, comlying with international standards, but with the added benefit that they contain virtually no sulphur, low levels of nitrogen-containing compounds, poly-aromatics, olefins, olefins and oxygenates, resulting in more environmentally friendly products than those produced via crude-oil refining [19].

Although the Sasol plants cannot be regarded as biorefineries, they are the largest plants in the world and have been producing almost 50% of the country’s requirements in terms of fuel. The operational experience of using this technology can, when applied to biorefineries, can contribute to satifying a range of products which have to comply with ever-stricter *environmental* requirements.

20.2.5 Concluding Remarks

An overview of the current state of biorefineries and the technologies they need was given. While there are a lot of options not only in the types of biorefineries available, that will mostly depend on the feedstocks and products required, but also the current state of their development. While some of the processes suggested for these plants are in common use, such as hydrolysis, others are still in their research phase, like the suggested algae plants. The project aim of being able to select different processes should therefore take the level of development of each process into account and be able to discern between these development stages.

20.3 Reducing Power Consumption in Helical Gear Drives Using Synthetic Lubricants: A Case Study

The use of *energy* efficient gear oils to reduce power consumption has been tested and shown to produce significant and measurable results. In a program that included a laboratory trial and an extensive in-service trial energy reduction of at least 2.2% have been demonstrated in helical gearboxes.

The potential impact of these savings if expanded to South African Industry could save in excess of 200 MW. This saving could have significant impact on the need to install additional generating capacity in the future. This case study shows a detailed methodology for the laboratory and in-service testing of *lubricants* that may reduce energy consumption.

Energy consumption is an increasingly important topic globally. Increasing electricity prices driven by demand and supply constraints have forced companies globally to initiate projects and measures that will reduce specific power consumption. In South Africa, this problem has been highlighted by recent supply constraints in which power cuts have been experienced. The availability of electricity will remain under pressure for many years as the country puts in place measures to increase installed capacity and replace or maintain existing capacity. This situation has lead to a need for increased electricity costs to partly fund the new capacity requirements.

The sustainable reduction in *power consumption* by all is one part of an overall strategy to reduce the overall need for more power. All areas of consumption need to be analysed and every small incremental saving can contribute to a reduced new capacity requirement.

20.3.1 Eskom's Energy Efficiency Drive

Eskom have embarked on an external and internal energy efficiency awareness campaign and various programs have been implemented to encourage savings. In some cases, as with the solar water heating and energy efficient motor projects, financial incentives in the form of rebates or discounts have been put in place to encourage take up of new energy efficient technologies.

Internally Eskom has a savings initiative which aims to save 1 billion KWh of electricity. Most of the initiatives to date have focused on savings from electrical applications such as energy efficient lighting and thermal insulation in households. More recently this program has been extended to look at process efficiencies and auxiliary or internal power consumption.

This paper reports the results of the testing of various synthetic gear oils in helical gear drives. The project was initiated to confirm claims by numerous vendors as to the energy reduction benefits of synthetic gear oils. In addition it was felt that independently verified data would encourage not only the use of this technology in-house but also encourage general industry and other large lubricant users to implement the findings.

Lubricant specifications generally do not have any requirements for energy efficiency. As such there are relatively few oils designed specifically with energy saving as a primary objective. An exception would be in the automotive arena where energy efficiency is a component of various specifications. This requirement is driven by the need to reduce fuel consumption, which in turn is driven by environmental requirements, i.e., the need to reduce exhaust emissions. Even with this in mind, not many users purchase these oils with the intent to reduce fuel consumption. No such requirements are in place to drive energy consumption in the industrial arena; however some marketers of synthetic and high performance oils have been promoting this as part of the benefits of their oils for some time. Most synthetic oils are marketed on the basis of extending oil change intervals and reduction in wear. Due to high differential cost versus standard mineral oils, synthetic oils have also been confined to extreme operating conditions, mainly high temperatures applications and extremely low temperature applications. Synthetic oils, for example, have been used for many years in compressor applications and are now a requirement in many modern engine designs. Nonetheless the increasing availability and use of *synthetic oils* has brought with it the possibility of reducing power consumption via the use of these oils.

In Eskom, a study was undertaken to identify the areas where energy reduction could be implemented on a continuous and sustainable basis. The amount of savings also needed to be measurable to have a long term significant impact. In addition, the type of application selected should be generic enough as to be applicable across the business but also applicable to South African Industry in general.

The main types of lubricant used in Eskom are turbine oils, hydraulic oils and gear oils. These three oil types account for 90% of Eskom's lubricant consumption in the Generation Group.

From an analysis of lubricant usage and lubricant applications in Eskom, gearing applications were identified as a potential candidate. Literature surveys revealed little guidance as to the extent of savings actually achievable. Most data was produced by *lubricant* vendors in laboratory tests and the few in-service tests described concentrated mainly on worm gearing or single applications. Based on the known mechanical efficiencies of helical gearboxes, a saving of about 0.5–0.75% per gear stage was considered possible.

The air cooled condenser at Matimba was identified as an ideal candidate site to test oils in gearboxes due to the large population of gearboxes in the condenser. Matimba's air-cooled condenser (ACC) has 288 *gearboxes*. These gearboxes operate continuously and form part of the drive train that powers large 9 m diameter cooling fans. The fans are used to provide cooling air to the condenser radiator banks where steam from the turbines is condensed before returning to the boiler.

20.3.2 Oil Selection

Numerous oil vendors, representing a wide range of lubricant technologies are represented in the South African market. Eskom wanted to identify which technologies, if any, could provide significant and provable savings. A number of oil types were identified for inclusion in a laboratory screening test. The main constraints in oils selection were the budget allowed for testing and the specific application constraints in service. A range of oils representing various synthetic types and grades were identified. Semi-synthetic oil was chosen as well as some high performance mineral oils. The reference oil chosen for the laboratory trial was an SAE 50 diesel engine oil. The engine oil was included as a reference oil as most of the gearboxes were using this oil in service. The engine oil was used on the recommendation of the contracted oil vendor due to high operating temperatures experienced in-service. This oil was changed to a standard extreme pressure gear oil for the baseline in-service trial.

It must be noted that specific additive chemistries for test oils were not identified in detail but rather the general base oil and additive types. The performance standards to which each oil complies were identified via data submitted by various oil suppliers in the form of technical data sheets and material safety data sheets. No aftermarket additives were considered as the use of these products is generally prohibited in Eskom.

The costs of synthetic oils are always a concern but this was not used as a criterion in selecting oils. No attempt was made to entertain all the oils on the market but rather to select a range of technologies from various vendors. No sample donations were allowed and all lubricants were purchased via the normal channels.

20.3.3 Laboratory Testing

In order to identify potential candidate oils and to verify some of the oil company marketing claims, 19 oils of different *viscosities* and oil types were selected for a laboratory trial. Testing was performed on a modified *FZG machine* at the Tribology Laboratory of the Department of Chemical Engineering at the University of Pretoria [20]. The modified FZG method was initially developed by this laboratory as a part of an earlier Eskom project to test open gear lubricants [21, 22].

The standard FZG machine (Figs. 20.1, 20.2) was modified to allow for constant temperature operation [23]. The modification was intended to measure the wear performance of lubricants at a constant temperature through increasing loads. The modification allows cooling water flow rate to be adjusted according to load and lubricant tested. This modification allows for the measurement of energy usage via the requirement for cooling water. A heat balance was developed to

Table 20.3 Lubricants for laboratory testing

ID. No.	Type	ISO viscosity grade
LUB 1	Synthetic (PAO ester)	460
LUB 2	Synthetic (PAO ester)	320
LUB 3	Synthetic (PAO)	320
LUB 4	Mineral oil (Semi –synthetic)	220
LUB 5	Mineral oil (Diesel engine oil)	SAE 50 (ISO VG 220)
LUB 6	Mineral oil	460
LUB 7	Mineral oil	220
LUB 8	Synthetic (PAO)	460
LUB 9	Synthetic (PAO)	220
LUB 10	Synthetic	460
LUB 11	Synthetic	320
LUB 12	Synthetic	220
LUB 13	Mineral	460
LUB 14	Mineral	220
LUB 15	Mineral oil (plus moly additive)	220
LUB 16	Synthetic (PAO)	220
LUB 17	Synthetic (PAO)	460
LUB 18	Synthetic (PAO)	220
LUB 19	Synthetic (PAO ESTER Blend)	220

demonstrate that heat generated via friction can be equated to energy consumption. It was also found in the laboratory trial that the measurement of temperature or heat generated by friction is a better and more reliable indicator of energy savings potential [24]. This is especially true when savings are low and measurements of savings are affected by fluctuating electrical currents. FZG *gears* are intentionally "poorly" designed in order to produce a result in the laboratory test [25]. The result is less-than-perfect gear meshing and fluctuating electrical currents. Table 20.3 is a list of oil types and grades included in the laboratory test.

The test was designed to compare various technologies and oil grades against the traditional lubricant selection parameters of load, speed and temperature. Each oil was put through the same sequence of tests. Each stage of the test was defined by a specific load stage, a specific set temperature and a specific speed. At the end of each stage, one parameter was changed and the test continued. A total of 5 stages constituted a test for each oil. Each test sequence lasted 3½ h. The total cooling water usage required to calculate the energy removed was recorded for each lubricant (Fig. 20.9).

Due to the short duration of the test the mass loss was too low for all lubricants to be considered significant. In addition, the power measurements recorded could not conclusively differentiate between lubricants. The heat removed via cooling water however produced significant results (Fig. 20.10).

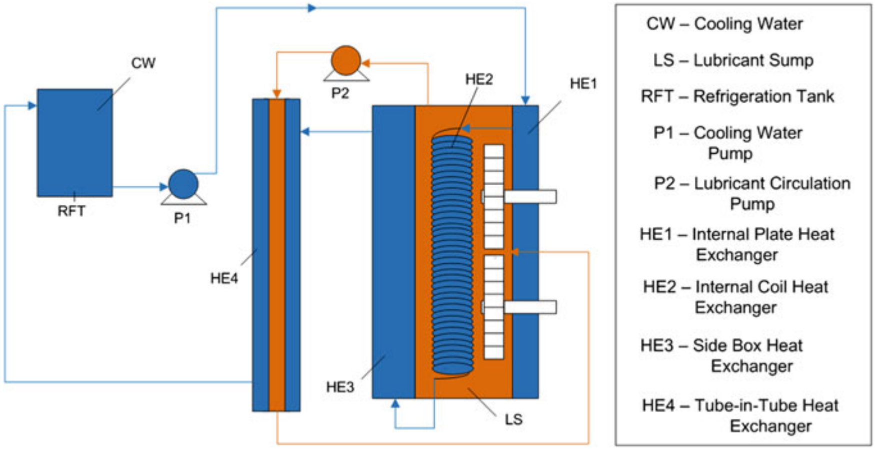
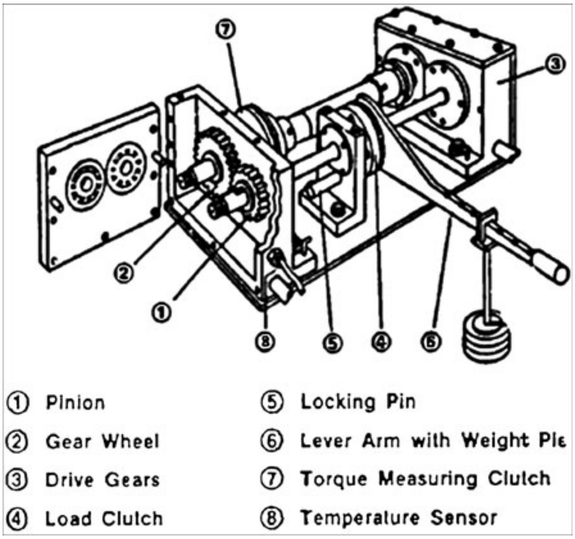

CW
RFT
P1
P2
HE2
HE1
HE4
HE3
LS
CW – Cooling Water
LS – Lubricant Sump
RFT – Refrigeration Tank
P1 – Cooling Water Pump
P2 – Lubricant Circulation Pump
HE1 – Internal Plate Heat Exchanger
HE2 – Internal Coil Heat Exchanger
HE3 – Side Box Heat Exchanger
HE4 – Tube-in-Tube Heat Exchanger

Fig. 20.9 The modified FZG layout showing cooling circuit and oil circuit [5]

Fig. 20.10 Standard FZG apparatus [25]



20.3.4 Laboratory Results

The graph shows that the heat removed differed significantly between the different lubricants. What was surprising was that not all *synthetic oils* performed well despite vendor claims. Nonetheless, in general the synthetic oils showed a lower energy requirement than the mineral oils. Some synthetic oils of the polyglycol type performed well but were excluded from the in-service trial for compatibility

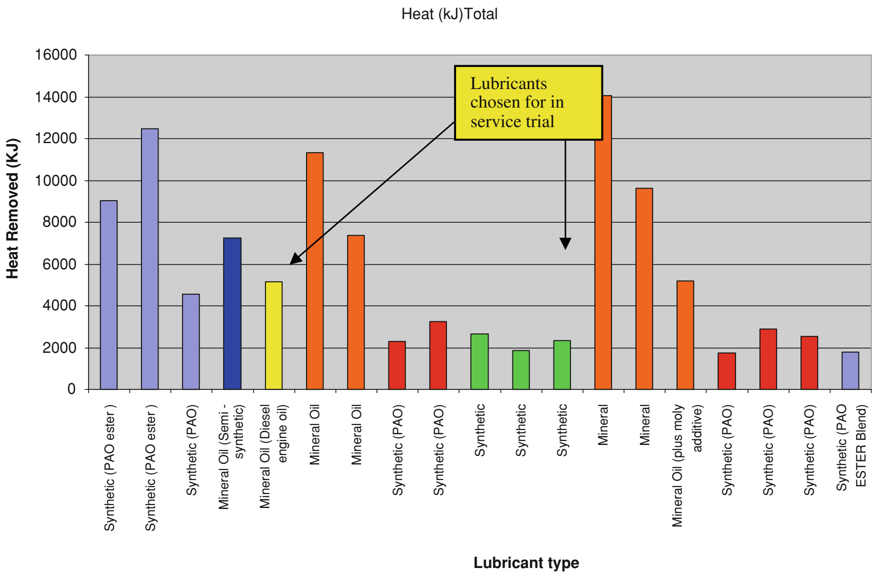


Fig. 20.11 Heat removed during laboratory testing

reasons. Three of the best performing polyalphaolefin type gear oils were selected for an in-service trial (Fig. 20.11).

20.3.5 *In-Service Trial*

The in-service trial of selected PAO gear oils was performed at Matimba Power station from June 2010 to December 2010. Three different oil brands were selected, with two different viscosity grades, an ISO VG 220 and an ISO VG 320.

Thirteen gearboxes, from two different gearbox manufacturers, were selected for the trial. Three older design *gearboxes* from manufacturer A and 10 new gearboxes from manufacturer B. The basic gearbox data is given in the table. Gearbox type A was originally installed during the 1980s and has been in service since then. Most of these gearboxes have been refurbished more than once and may be replaced in future by a more modern and efficient design. In order to ensure the trial was not compromised the 3 A type gearboxes were fully refurbished before the trial started (Table 20.4).

The 10 new gearboxes, of the B design, were brand new gearboxes of the same basic design intended for Eskom's two new coal-fired power stations, namely Medupi and Kusile *Power Stations*. These gearboxes are much lighter in weight and have a significantly lower oil volume compared with the original gearbox. Gearbox A has a 160 L oil sump whilst Gearbox B has a 35 L oil sump. Both gearboxes transmit the same power, approximately 220 KW.

Table 20.4 Test gearbox data

	Gearbox A	Gearbox B
Motor Power (KW)	270	270
Gear Ratio	11.84:1	11.76:1
Oil Sump Volume	160 l	35 l
Method of lubrication	Circulation, no cooling	Circulation with in-line filtration and no cooling
Average sump temperature	70°C	95°C

The basic test methodology was simply to test all gearboxes on standard extreme pressure gear oils and to measure the current drawn as well as the bulk oil and ambient temperatures. The data would be gathered after a minimum run-in period of about 1 month. After baselines were verified, the oil was to be changed to one of the identified synthetic oils. After a period of one month to allow for any changes and to comply with external measurement and verification criteria, the same data would be collected again.

Data collected included measurement of the current drawn by each motor as well as the measurement of bulk oil temperature and ambient air temperature. PT100 probes were installed in all test gearboxes and a data logger was attached to collect ambient air and bulk oil temperature readings at regular intervals. As with the *laboratory trial*, it was expected that the synthetic oils would show a significant, measurable drop in sump temperature. What was of more importance was the rise in oil temperature over ambient temperature.

Electrical current is measured continuously by the *power station* and recorded on the plant database. It is possible to obtain historical data for many years of operation as well as the average ambient temperature on each day. The ambient temperature is logged by the plant operators as the temperature has a direct influence on the volume and quality of cooling air available to the condenser. The power drawn by the fan drops as the temperature increases, and increases as the temperature drops. Essentially the power requirement is a function of air density.

An analysis of the current drawn on a number of *gearboxes* before the test showed that current could fluctuate as much as 5% either way, giving a power fluctuation of about 10%. This caused initial concern as the anticipated saving before the test began was expected to be in the order of 1–1.5%. There was some doubt as to whether an average current drop of 1.5% would be detectable in the scatter of measurements. Nonetheless, it was expected that due to smoothing of data, the oil temperature measurements would be a better and more reliable indicator of *energy savings*.

In addition to the temperature and current measurements, vibration baselines and oil samples were taken of the synthetic oils at the start of the trial. These gearboxes will be monitored using vibration analysis and oil analysis on a regular basis until an oil change is required. This is done in order to detect premature gear wear and the life of the synthetic oils in service at the operating temperature. This data will be used to determine planned oil change intervals. The oil change interval is also required to finalise the life cycle costs of these oils. To date neither oil nor vibration data show any significant or noticeable changes.

All test boxes were installed on different dates over a 3 month period. The main constraint being the availability of maintenance personnel to install gearboxes. Due to production constraints it was not possible to stop any particular generating unit to install 13 test gearboxes. As mentioned earlier, the station has 288 gearboxes installed in the air cooled condenser, and there is a regular failure rate due to the age of the station. As gearboxes "fail" or are removed from service for maintenance, they were replaced with test gearboxes. Every attempt was made to try and locate these boxes in the same general area but this was not possible. The result is that the running-in period of these boxes ranged from less than one month to as much as 3 months. This was considered insignificant based on the normal life of such a gearbox, i.e., greater than 100,000 operating hours.

All test boxes were filled with standard ISO VG 320 extreme pressure gear oil, typically meeting DIN 51517 Part 3 CLP requirements. The oil grade used was suitable for both gearbox designs. In fact both gearbox designs can operate on an ISO VG 220 oil. The intention of using the higher grade was to cater for the normally high operating temperatures in Gearbox A. Gearbox type A was found to fail the required thermal rating for the application but has remained in-service for many years with a reduced oil change interval.

All oil vendors participating in the trial were allowed to share data relevant to their oils being tested. In order to maintain objectivity and transparency, Eskom did not accept any oil donations and all samples tested were purchased through normal purchasing channels.

The current oil supplier decided to employ the services of an external M&V (measurement and verification) consultant to measure and verify the savings recorded during the trial. Eskom have established a process whereby *energy savings* need to be externally verified in order to be accredited. Although this was initially not a requirement for this trial, it was decided to allow the external consultant full access to all data. The consultant was trained and accredited by Eskom's demand side management process. The requirements imposed by the consultant were that data for baseline purposes needed to be gathered for at least one month prior to the oil change. In addition, it was interpreted that the gearboxes would have to operate for a minimum of one month before the new data was recorded. An additional requirement, again not part of this test, is that data has to be verified annually for a 5 year period after the change.

In the case of this trial, the intention was to establish whether energy could be saved by correctly choosing and using synthetic gear oils and to verify the extent of this saving. This objective was met as is discussed.

20.3.6 Power Savings

Data gathered during the trial was captured in weekly intervals due to limitations of the data recorders. There was no limitation on data available for current drawn; however occasional glitches resulted in corrupted data from time to time. The result is that to ensure repeatable and consistent results, data was gathered more than once over a six month period.

The graphs and tables show the average calculated power consumption for each gearbox for specific weeks during the trial; from the graphs it is evident that the power consumption using mineral oils was consistently higher than that of the synthetic oils. This data is actual data and has not been corrected for any ambient temperature influences. On average, a power consumption drop in the order of 4.64% was noted. Table 20.5 is a summary of *power consumption* averaged for all the data recording periods.

The power consumption shown in graphs (Figs. 20.12, 20.13) is the average for each gearbox for a specific week of recorded data. The weeks reported here coincide with the same weeks in which *temperature* data was logged. The external verification was based purely on electrical current data and did not coincide with the temperature data collection periods.

From the graphical results it is clear that power was reduced with the introduction of *synthetic oils*. The average weekly differences can be attributed mainly to differences in ambient conditions. No changes to the plant configuration were allowed when replacing the mineral oil with synthetic oils. The differences between the various gearboxes can be attributed to the location of the gearbox in the condenser. In this case air flows differ depending on the specific installed location within the condenser.

The average *power savings* documented by the external M&V verifier was 3.8%. From this perspective the results are in agreement with each other. It must be noted that the external verification used an average of one month's data for the base line and one month's data for the power consumption after the oil change. The periods chosen by the external consultant differed slightly from the results presented here, however after comparison of results it was agreed that the basic methodology used to analyse and interpret the data was consistent between the two parties.

In order to determine the clean or net energy savings it is necessary to take into account changes in efficiency of the motor and gearbox drive system due to the drop in power required. In effect the motor has a specific power factor versus load profile. Data on the specific motors showed that the motor average power factor may be affected by the change in required or absorbed power. In essence the motor becomes slightly less efficient resulting in higher power consumption. To allow for this, on advice from Eskom in-house electrical engineers, a power factor of 0.86 was used for all calculations using mineral oil. For synthetic oils, due to the drop in absorbed power, a power factor of 0.85 was used in power calculations. On average this would adjust the gross power saving by about 1%.

Table 20.5 Average power consumption for mineral and synthetic oils

Gearbox number	Manufacturer	Oil	ISO VG	Average power (kW) (mineral)	Average power (kW) (synthetic)	Ave min–ave syn	% diff
3-22-20	Gearbox A	Synthetic 220	220	245.38	234.91	10.47	4.27
3-22-50	Gearbox A	Synthetic 220	220	223.48	213.69	9.79	4.38
3-23-20	Gearbox A	Synthetic 320	320	220.35	210.07	10.28	4.67
3-23-60	Gearbox A	Synthetic 220	220	216.60	203.36	13.24	6.11
3-24-20	Gearbox A	Synthetic 220	220	228.04	217.05	10.99	4.82
3-24-40	Gearbox A	Synthetic 220	220	234.78	224.53	10.25	4.37
3-31-10	Gearbox A	Synthetic 320	320	224.69	214.23	10.47	4.66
3-31-20	Gearbox A	Synthetic 320	320	210.91	201.12	9.79	4.64
3-32-60	Gearbox A	Synthetic 320	320	210.30	203.28	7.02	3.34
1-22-50	Gearbox B	Synthetic 220	220	251.77	237.04	14.73	5.85
2-22-30	Gearbox B	Synthetic 320	320	204.13	195.81	8.32	4.07
3-31-40	Gearbox A	Synthetic 320	320	203.41	194.77	8.64	4.25
3-33-20	Gearbox B	Synthetic 220	220	228.83	217.58	11.25	4.92
							4.64

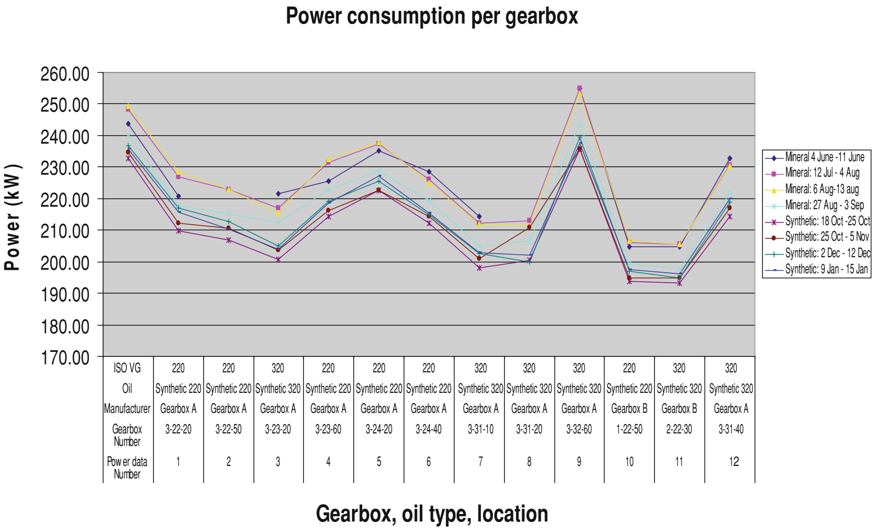


Fig. 20.12 Gross power consumption

In order to compensate for ambient *temperature* differences a factor of 0.3237% reduction was applied for every degree increase in average ambient temperature. This figure is derived from the change in air density per degree at an altitude of 1,400 m above sea level. This correction is in line with the air cooled condenser OEM design philosophy. In the case where ambient temperature dropped on average, the savings were increased accordingly. Where possible, data was

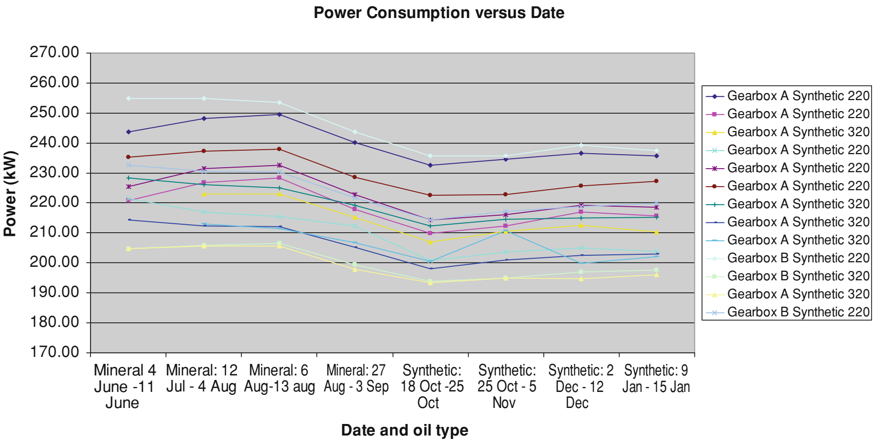


Fig. 20.13 Gross power consumption

Table 20.6 Corrected power consumption for end August and beginning December 2010

Oil gearbox number	Gearbox number	Power mineral oil 27/8 -3/9	Power synthetic oil	% drop in power	Change in ambient temp	Correction for change in ambient (%)	Nett Power Saving (kW) (%)
7	3-24-20	222.77	218.65	−1.8	−1.78	−0.6	2.4
8	3-24-40	228.66	225.14	−1.5	−0.38	−0.1	1.7
6	3-23-60	212.40	204.21	−3.9	0.91	0.3	3.6
4	3-22-50	243.80	238.71	−2.1	−0.07	0.0	2.1
3	3-22-20	240.19	236.20	−1.7	−0.36	−0.1	1.8
10	3-31-20	205.08	202.19	−1.4	0.37	0.1	1.3
9	3-31-10	219.33	214.77	−2.1	−0.01	0.0	2.1
5	3-23-20	215.12	211.87	−1.5	−1.26	−0.4	1.9
11	3-31-40	197.80	194.56	−1.6	0.49	0.2	1.5
12	3-32-60	206.64	199.33	−3.5	−0.16	−0.1	3.6
13	3-33-20	221.73	218.51	−1.5	−0.55	−0.2	1.6
1	1-22-50	243.80	235.62	−3.4		0.0	3.4
2	2-22-30	199.39	196.42	−1.5	−0.05	0.0	1.5

selected where ambient temperature would have had little or no effect on the resultant drop in power consumption. This approach is different to the formal M&V process in which only gross or actual power measurements are used. The results here are therefore conservative but realistic and in line with what were expected before the trial began.

Table 20.6 shows results for the last week of August 2010 and the first week of December 2010. These two weeks were chosen after carefully studying load and data from all gearboxes. The data for these weeks were not influenced significantly by load changes and data recorded was by and large free from anomalies.

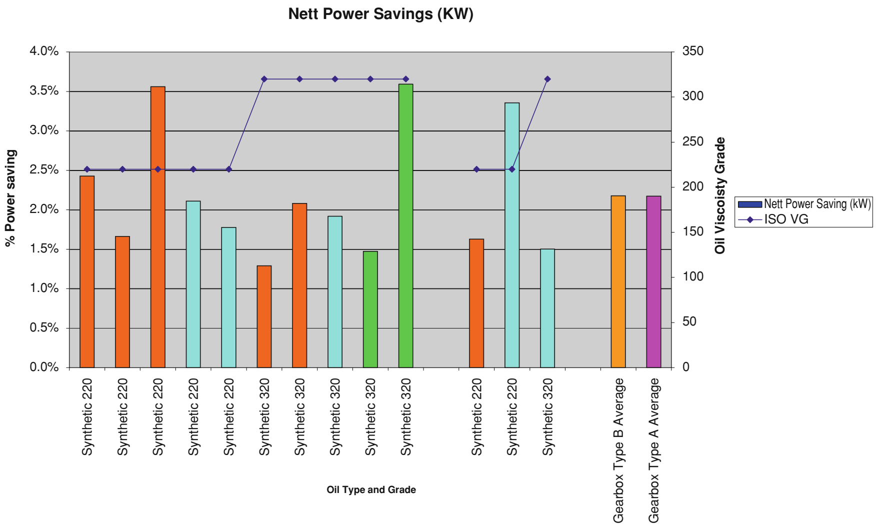


Fig. 20.14 Net power savings after temperature Correction

All *gearboxes* ran steadily at a relatively constant load for the entire duration of the trial period. In addition ambient temperatures were not significantly different.

From Table 20.6 and Fig. 20.14, the average nett power saving per *gearbox* can be calculated to be 2.2%. This is below the gross saving of 3.8% verified externally and below the average gross power drop of 4.64% using the actual current drawn or absorbed power figures. The nett saving is however in-line with the 1.5% savings predicted before the test program began.

20.3.7 Temperature Drop

In addition to measuring current, the bulk oil temperature and ambient temperature were recorded. From the results in Table 20.7 it is clear that the rise in temperature above ambient is significantly lower using synthetic gear oils. On average there is a 6°C drop in operating temperature. It appears that the percentage drop in oil temperature is roughly 3 times the drop in *power consumption*. There is no correction for this value as it can be seen from the graphical data that the operating temperature tracks the change in ambient temperature. This confirms that temperature can be a more reliable indicator of energy savings in applications where the percentage current savings are low.

Two different *grades of oil* were used in the trial, an ISO VG 220 and an ISO VG 320. From Fig. 20.15 it is clear that the lower viscosity grade provides additional power savings. This illustrates the need to ensure correct viscosity grade selection up front. Due to the higher viscosity index associated with the synthetic

Table 20.7 Bulk oil, ambient and oil temperature rise

Gearbox number	Oil	Bulk oil temp (mineral oil) °C	Ambient temp (mineral oil) °C	Oil temp rise (mineral oil) °C	Bulk oil temp (synthetic oil) °C	Ambient temp (synthetic oil) °C	Oil temp rise (synthetic oil) °C	% drop in bulk oil temperature rise (%)
3-24-20	Synthetic 220	78.83	29.13	49.70	70.73	27.35	43.38	9.1
3-24-40	Synthetic 220	76.48	29.15	47.33	70.28	28.77	41.51	11.5
3-23-60	Synthetic 220	75.16	30.20	44.96	69.08	31.11	37.97	17.6
3-22-50	Synthetic 220	71.83	28.42	43.41	70.58	28.35	42.23	2.5
3-22-20	Synthetic 220	75.39	28.23	47.16	70.37	27.88	42.49	9.1
3-31-20	Synthetic 320	71.34	26.98	44.37	68.17	27.35	40.82	8.8
3-31-10	Synthetic 320	74.77	28.55	46.23	68.79	28.54	40.25	12.9
3-23-20	Synthetic 320	72.80	29.13	43.66	67.37	27.88	39.50	6.7
3-31-40	Synthetic 320	71.93	27.77	44.16	68.47	28.26	40.21	10.1
3-32-60	Synthetic 320	74.82	29.39	45.43	69.66	29.23	40.43	10.7
3-33-20	Synthetic 220	94.00	28.36	65.64	89.50	27.81	61.69	5.2
1-22-50	Synthetic 220	92.03	26.85	65.18				
2-22-30	Synthetic 320	88.54	26.91	61.63	88.10	26.86	61.24	0.6
	Gearbox Type B Average	74.51	28.70	45.64	69.35	28.47	41.03	9.6
	Gearbox Type A Average	91.52	27.37	64.15	88.80	27.34	61.46	4.1

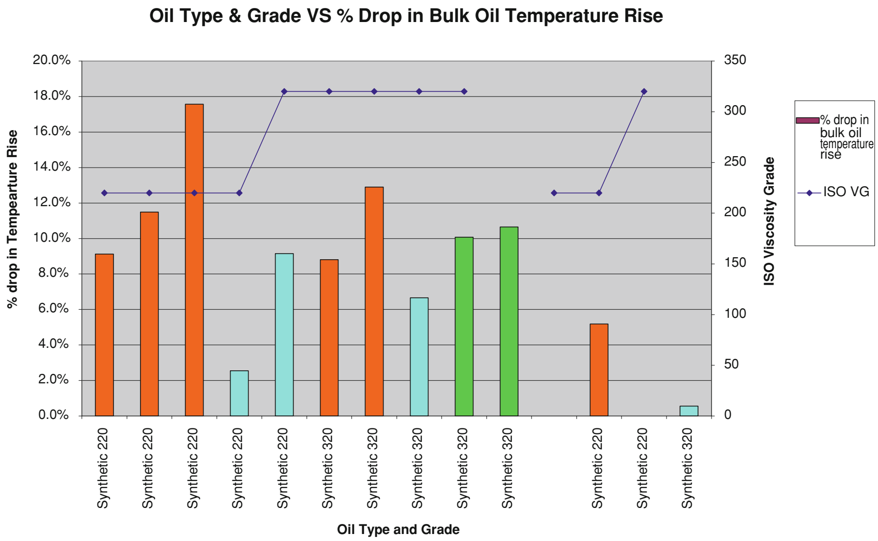


Fig. 20.15 Percentage drop in temperature using synthetic oils

oils and the lower operating temperature it should be possible to further reduce the oil grade and achieve higher savings without compromising gear protection.

As is clear from the results presented above, there is both a power saving and a temperature drop. The temperature drop should also equate to longer oil life and future reduced oil consumption in these gearboxes.

20.3.8 Cost Savings

The potential energy savings at Matimba have been calculated at 1,425 kW if all 288 gearboxes are converted to the *synthetic oil*. This equates roughly to 11,500,000 KWh per annum. In Eskom, the conservative potential savings could be as high as 20 MW or 140,000,000 MWh if all major gearboxes were converted to a suitable synthetic oil. One of the major considerations is that the use of these oils would require a significant change in mindset and maintenance practises to allow the oil to achieve its full life without the need for an early oil change.

In the South African market Eskom's oil usage is estimated at less than 0.5%, whilst the *mining industry* alone accounts for at least 15–20%. This makes the potential for energy savings potential a factor of 30 times higher in the mining industry. It is difficult to estimate all sectors but potential savings in gearing applications alone could exceed 200 MW and be as high as 600 MW. It is not likely that all these applications would be converted but even a low percentage uptake would have a significant impact in reducing power consumption consistently [26].

20.3.9 Conclusions

A number of conclusions can be drawn from the laboratory and in-service trials, they are listed:

- Correctly selected synthetic oils of the polyalphaolefin type can reduce power consumption by at least 2.2% in efficient helical gearboxes. Gearboxes with lower efficiencies should see much higher savings.
- It is advisable to institute a clear test protocol and oil screening process before implementing synthetic gear oils.
- There is huge potential for power savings nationally if all major users implement a similar program.
- Temperature is a good and reliable indicator of *energy savings*.
- Other application types should be explored and tested for energy savings.

20.4 Metal-Working in South Africa: A Green Tribology Perspective

South Africa is a country richly endowed with minerals and coal energy and with a modern industrial production base. This enables us to produce base metals such as steel, stainless steel, yellow metals (copper, brass, bronze etc.) and aluminum, ultimately ending up in manufactured final consumer or industrial products. From the virgin metal to the final product, diverse *metal-working* operations are performed which invariably involve the use of either neat or water soluble oils applied in copious quantities with often negative consequences to the environment. Traditionally, the lubricant was a mineral oil and the disposal of spent neat oil is by incineration in a conventional boiler. Disposal of spent water soluble oil however, is more of a problem because of smaller volumes and longer distances between source of oil and facility to separate the oil and water. Hence the use of evaporation ponds to dispose of such waste oil. Unfortunately, the easier but environmentally unacceptable way is to dispose of such waste by discharging it in an open drain or municipal sewer system. With the rapid urbanisation of our population and South Africa being a water scarce country, such disposal of neat or soluble oil has severe pollution potential for our rivers, dams and underground water resources.

The South African manufacturing industry, like elsewhere in the world, is confronted with the negative impact of spilled *lubricant* on the production floor influencing workers' health (skin disorders such as dermatitis, tramp oil mist etc.) and the cost of keeping production equipment and the production floor free from excess oil with detrimental consequences.

The cleaning of parts from the conventional neat/soluble oil manufacturing plant covered with liberal quantities of oil, results in higher cost of cleaning and requires costly cleaning machines, again impacts on the environment as spent washing fluid must be recycled or disposed of. Another cost factor is tool life, because the cost of tooling is playing an increasingly more important part of production cost as more sophisticated tools are continually being introduced with modern coatings. The change of tooling not only implies a direct cost, but also the cost of down time for tool replacement and the loss of production when running in the tool in ramping up to full production rate.

Being part of a highly competitive global production environment, South African industry is continuously under pressure to keep costs down. As the cost of lubricants, tooling and associated in the European field of automotive parts production approaches 20% [27], more and more attention will be given to cost saving lubrication techniques, including the cost of energy.

20.4.1 Introducing Minimum Quantity Lubrication

Seen against this background, a South African company, Producut Lubrication Technologies started with the introduction of *Minimum Quantity Lubrication (MQL)* in the early 1990s with a “home brewed” approach to address the realities of metal and part production in the African environment where realities are often remote from First World operations but not escaping the competition of a modern global manufacturing village.

The application on the technique starts with primary metal production (e.g. at smelters, steel rolling mills etc.) through semi-products (rolling mills, extrusion plants, pipe mills etc.) ending up as pipes, machined parts, fabricated products, produced via milling, turning, stamping, forging, pressing etc. in our homes, our buildings, our mines, our automobile plants, defence production plants, electrical industry etc. In almost all these metal-working operations, lubrication of some cost is required.

The introduction of the MQL technique was prompted to address the negative consequences of conventional lubrication by using extremely small quantities of lubricant, the cleaning up of the production environment and eliminating spent fluid disposal, reducing the impact on production personnel etc. Costs come down by using far less lubricant, having a better tool life, reduced part cleaning costs and no spent oil disposal costs. *Micro-dosing* also facilitates production logistics in view of small volumes to be handled. Energy savings are achieved by eliminating fluid circulation/filtering equipment and by keeping tools sharper for longer times. In short, the dramatic reduction of the lubricant carbon footprint and environmentally friendly production floor and of course, bottom line cost savings, are the real drivers for introducing MQL in the market place. Our case study (below), aims to practically illustrate these claims.

20.4.2 Use of Plant Oils

A further milestone in our journey to make a contribution to *green metal-working* [28], came with the introduction of plant oils and oils derived from plant (renewable) feed stock, such as synthetic esters. We started our MQL with conventional mineral oils but soon realised its negative qualities. In MQL, the lubricant is applied in an open environment, stressing the need for environmental–friendly qualities of a lubricant. We then changed to plant oils/synthetic esters to enjoy the benefits of almost zero toxicity, safety (high flash points), high smoke points, good biodegradability, wide temperature application ranges and of course good lubricating properties. This was verified by film strength determination in an Optimol 1 SRV® tribometer simulating MQL continuous flow on lubricant on the test piece. Furthermore, costs of plant oils compares favourably with that of mineral oil and is readily available from our soil. However, we had to contend with the negative features of plant oils i.e. its poor resistance to oxidation stability and polymerisation to create rubber-like deposits. Thanks to modern anti-oxidant packages, it is possible to inhibit these negative features substantially. When severe metal-working is performed in the boundary lubrication regime and high rates of metal removal are required, we blend in Extreme Pressure and Anti-Wear enhancing additives, meeting the US FDA's clearance for formulating FDA approved lubricants.

20.4.3 The Case Study

In the early 1990s [29] a trial was performed at an *aluminium smelter* on a continuous horizontal slab casting line, which was fitted with a circular saw ("old saw") and lubricated by soluble oil being sprayed liberally onto the blade. The production floor and environment was pretty wet and housekeeping was difficult and occasional incidences of skin disorders (*dermatitis*) were reported by operating personnel. Accurate data on operating parameters on the saw was recorded.

Then an identical new saw ("new saw") was fitted onto this line but this time with an MQL lube system supplying neat synthetic oil. Again accurate data on saw and lubricant was collected. Table 20.8 shows the cutting performance of both saws, cutting 99.7% aluminium cast ingot material, 490 × 1675 mm, using a TCT blade 1870 mm diameter with 18 mm cutting kerf. The cutting parameters (feed and speed) pertaining to the sawing operation was in essence the same for both saws.

The outcome of this trial bears out the virtue of a "green tribology" operation i.e.

- The volume of neat lubricant used was almost 600 times lower when using the MQL technique, drastic reduction in carbon foot print
- The cost implications of lubricant usage (71:1) speaks for itself, which makes the pay-back period for the MQL equipment installed on the saw months rather than years, making it the financial/production man's dream with a normal pay-back period of 3–5 years.

Table 20.8 Cutting performance of two saws

Parameter monitored	New saw (MQL lube)	Old saw (Soluble lube)	Ratio new:Old
Duration of trial	12 months	12 months	1:1
Tons sawn (Metric Tons)	43148	43148	1:1
Lubricant consumed (Litres)	110	65100	1:592
Cost of Lubrication (p.a.)	**$628**	**$44,880**	1:71,4
Ave Blade Changes (p.a.)	18	69	1:3,8
Blade repair cost (p.a.)	**$1,323**	**$14,857**	1:11.2
Lube Disposal cost (p.a.)	Nil	**$2,800**	–
Total Cost	**$1,951**	**$62,537**	1:32

Note: The above amounts refer to US dollars

- The significant reduction in blade changes (1:4) agrees with our findings in cutting operations. In our mind this can be attributed to the cutting oil with good lubricity, high film strength and anti-wear properties keeping the cutting tip sharp over longer periods.
- A last but significant advantage of *MQL* is that saw chips (18 mm kerf) can in the case of MQL be recycled by simply compressing chips into a block for downstream re-melting. In the case of soluble oil cutting, it was necessary to dry the chips before recycling could take place and is normally sold at scrap prices as drying costs were too high.

20.4.4 Practical Applications of MQL

20.4.4.1 The Aluminium Value Chain

Aluminium processing starts at the smelter producing molten aluminium which then goes to the cast house where it is cast in either slab or T-Bar in a horizontal casting machine or in a vertical cast into poles (Fig. 20.1). Our involvement started with mould *lubrication* of the casting of T-Bar material where lubrication plays an important role when just solidified T-Bar is moved from the mould and where the mould release properties of a lubricant are required to allow a smooth flow of aluminium in the cast. A break in the cast results in considerable cost, hence the necessity for reliable dosing equipment and lubricant being plant oil (Fig. 20.16).

Our real challenge came when we introduced MQL on a saw cutting cast ingot or slab, as described in the above case study. Again lubrication of the sawing operation was of major importance as the saw moved with the cast ingot from the melting furnace. A jam in the cut would result in aborting the cast and considerable cost of re-starting the cast cycle. We shortly afterwards introduced the MQL cutting on smaller circular saws at the cast house where pole-like solid aluminium castings is cut into logs for downstream use by extruders of aluminium profiles.

Fig. 20.16 Inside the T-Bar cast house (Courtesy: Hertwich Engineering)

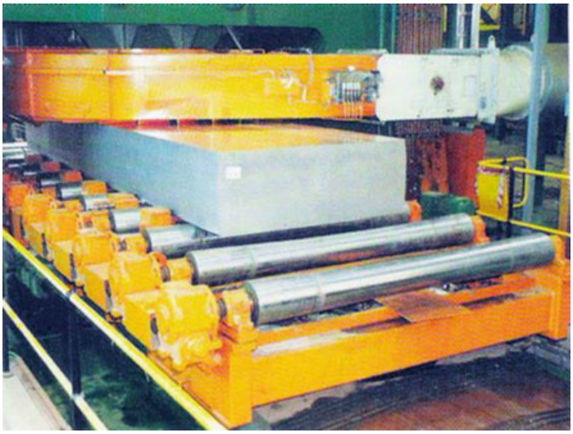


Fig. 20.17 Scalping Alu cast ingot

At the aluminium rolling plant, cast ingot is rolled down to plate sheet and foil. The process starts with a cast ingot either from virgin material or from scrap, and the first step is to remove the hard aluminium oxide layer from the top, the bottom and the sides of the cast ingot. The operation is very severe as cuts of up to 18 mm deep are taken and the rate of metal removing is very high. When we got involved, the scalper in question used copious quantities of neat oil and it impacted on the production environment in that excess oil was not only a menace to the production floor, but it also caused air pollution when oil-soaked chips were burnt off in the re-melt furnace. Furnace linings also suffered as a result of this excess oil. We managed to "dry" out this operation and today *scalping* is performed with the MQL system and the problems pertaining to a clean environment and a recycling of chips without excessive cutting oil have been solved (Fig. 20.17).

On the rolling mills, MQL pays an important role as absolute minimal quantities of lubricant are required for the lubrication of wheel cutters without

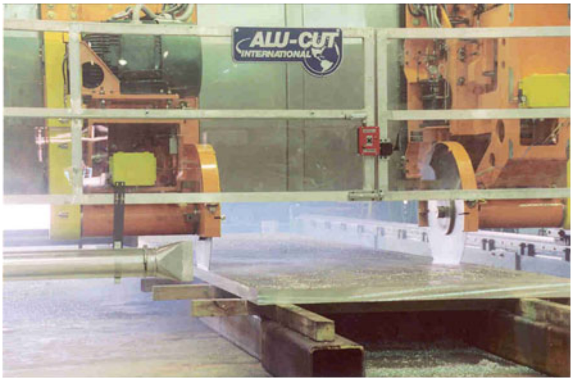


Fig. 20.18 Cutting stacked Alu plate (Courtesy: Hulamin Ltd and Alu-Cut Inc)

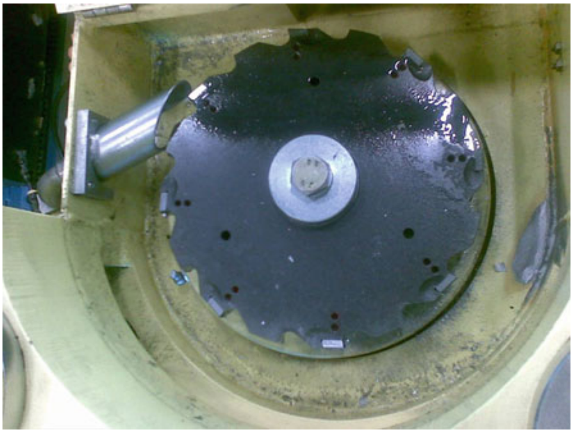


Fig. 20.19 Edge milling of cast Alu plate on casting machine

depositing oil on plate etc. causing downstream stains resulting in rejected material.

When it comes to cutting the rolled aluminium with guillotines or with circular saws (Fig. 20.18), MQL plays its role of keeping the *cutting* edges sharp, to give a good finish to the cut, avoid the build up of aluminium on the tools whilst avoiding soiled products ready for packing to the end user. In modern day plate production, the plate casting technique is used where molten aluminium is directly cast into plate form in the casting machine and the plate exiting from the machine is trimmed on its edges with controlled MQL lubrication (Fig. 20.19). This eliminates the risk of *stains* on the material, protects the cutters, makes housekeeping around the machine easy and allows off-cut material to be recycled without drying.

Concerning the recycling of aluminum scrap, either from own production or from scrap metal vendors, the material has to be cut into small strips in a shredding machine and then into small blocks, ready for use in the re-melt operation. Without

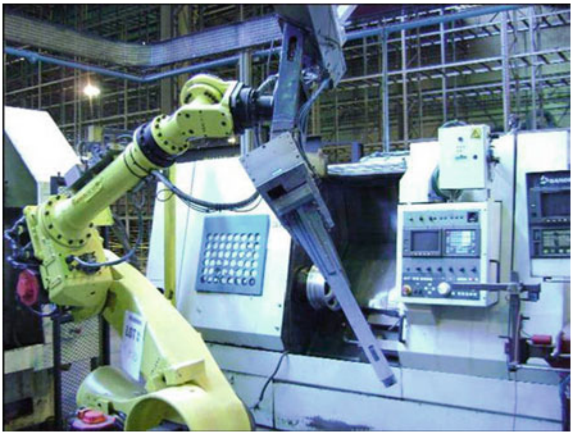


Fig. 20.20 MQL in alloy wheel turning

lubrication, severe pick up of aluminium on the cutting tips of these two machines will occur, disrupting the production process.

In the re-melt of aluminium, an important feature of our additive package in the plant oil/ester lubricant is the absence of any metals to avoid metal building up in the molten re-melts, hence the importance of ash-less additives in the lubricant.

We introduced MQL to lubricate a set of large bearings on a rolling mill where contamination of the oil from the bearings soiled the rolled stock in the mill with dire financial consequences. We use air as a carrier and MQL as the source of minute quantities of stain free neat *lubricant* to keep the bearings properly lubricated, continuously replacing the lubricant inside the bearing

Now we reach the downstream processing of aluminium to create extrusions at the aluminium extruder company. MQL is imminently suitable to cut aluminum logs (diameter up to 213 mm) into smaller billets which will be converted into extrusions in the press The fact that the cut billet is free from moisture and almost oil free, facilitates the heating thereof before entering the chamber of the press. Cutting of extruded profiles into lengths at the end of the extrusion cycle is another excellent application of MQL, as cutting of profiles requires sharp cutting tools and very little lubricant with low staining properties, remaining on the cut profile. When profiles require heat treatment, the manual removal of excess oil to avoid lube stains on heat treated items is costly and time consuming. With MQL, we succeeded in avoiding this scenario.

A major project which we tackled was the replacement of soluble oil cutting with MQL in an alloy wheel manufacturing facility (Fig. 20.20). The cast wheel with 9–12% silicon content is highly abrasive and chips have the tendency to weld onto the *cutting tool*. Cast wheels are first cut to size in a turning operation and then stud holes are drilled in the casting. The rate of metal-working is very high and we had to contend with the problem of stringy chips interfering with the spray of the lubricant in the MQL mode onto the working surface. We employed a

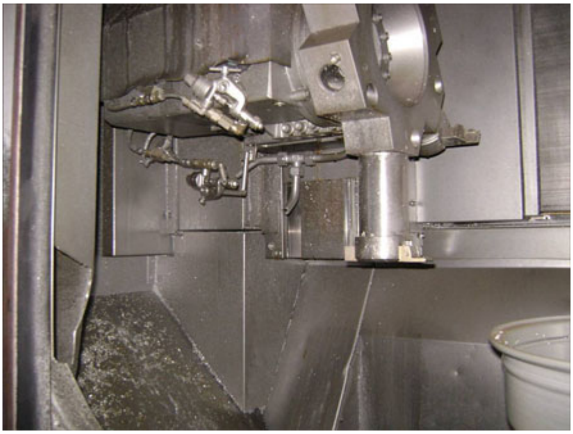


Fig. 20.21 Special spray gun used in alloy wheel turning

special spray gun that was able to spray lubricant in accurately controlled drops onto the cutting face in a remote fashion (Fig. 20.21).

A major change was the introduction of MQL in high speed stud hole drilling operations. The rate of metal removal was high, the aluminium highly abrasive and removal of chips critical. We were however fortunate to supply lubricant in MQL mode through the centre of the drill and later contended with a faster drilling cycle by adding smaller quantities of water together with the MQL lubricant. The elimination of copious quantities of soluble oil as lubricant had a significant impact on the air quality in the plant, especially as hot humid conditions gave rise to rapid bacterial growth in the soluble oil. The ultimate benefit was the elimination of the frequent disposals of spent lubricant at considerable cost, and having an improved finish and better tool life as bonuses of the MQL venture.

The use of MQL *lubricated drilling*, tapping, milling etc. operations of *aluminium* materials in diverse engineering applications, is well established and in use in our local manufacturing industry.

20.4.4.2 Yellow Metals

Virgin copper is produced by electrolytic refining with *copper* cathode material leaving the refinery. When converting copper into flat semi's (sheet, plate etc.) or when producing profiles or tubes, MQL starts to play its role. The same applies to converting copper scrap into extruded or cast billet material. Cutting of hot cast billet material in a casting machine with MQL, proved to be a cost efficient way of changing cast ingot into logs. The elimination of water in a molten metal environment added to safety and good housekeeping. Like in the aluminium industry, cutting of cast logs into billets for extrusion operations (e.g. producing copper pipes, brass profiles etc.) was performed with MQL. Likewise, the cutting of small billets and the creation of small copper/brass products like valves, taps etc. by hot forging, is successfully performed by applying micro-quantities of lubricant, often replacing graphite in oil as lubricant, the latter producing unwanted carbon monoxide. When it comes to producing small delicate parts for use in electrical and defense industries, MQL proved its value in drilling, tapping and blanking operations to giving better tool life, improving the quality of the finished product and saving on part cleaning costs.

In coin production, chips from scalping of ingot (containing high percentage of nickel) can be economically recycled because minute residual lubricant from MQL making re-melt feasible whilst water wet chips requires costly drying before re-melting. Tool life also benefited from small drops of lubricant being applied in a continuous mode.

Where aluminium is a relative soft material with a low melting point, copper is a much harder material with higher proof stress and hence we had to change our *chemistry* of our lubricant to accommodate harsher conditions to perform the plastic deformation of the chip in the cutting zone. In particular, smoke point of the oil had to be carefully evaluated to avoid MQL contribution in a negative way to the health in the production environment.

20.4.4.3 MQL in Steel Working Operations

Steel finds wide application in our manufacturing industry ranging from automobile parts, construction, building, defense, building etc. At present, the use of MQL in *steel working* processes is limited to working of light products because of the limited cooling available when using MQL. High temperatures in the cutting zone [30] caused by the high proof stress of the steel being worked, coupled to the low heat dissipation characteristics of steel, mitigates against the use of MQL in working of solid steels. MQL however is very useful in cutting steel tube in tube mills as conventional water soluble fluid (mill fluid) enters the pipe often causing downstream spilling of fluid in handling/processing operations. In blanking and pressing of steel parts, MQL with plant oils is gaining ground as a substitute for conventional heavy chlorinated paraffins which are environmentally unacceptable substances [31]. However to cope with these stringent demands placed on plant oils when working steel, sulphurized esters and increased EP/AW additives were blended into the plant base oil, This lubricant formulation has been in use for more than a decade with much success.

Robotic drilling and cutting of a steel parts using the MQL technique is very successful as the dispensing nozzle(s) moves freely with the robotic arm as there are no circulation of fluid or spillage of excess oil on the parts/robot.

20.4.4.4 Stainless Steel and MQL

A very successful product range being produced in South Africa, is catalytic converters and exhaust systems for automobiles produced from stainless steel. As the platinum, the chrome and nickel all comes from our soil, cutting and pressing of parts for catalytic converters are widely performed using the MQL technique.

We often use remotely positioned *spray* guns to shoot accurately controlled minute drops of lubricant into the press thereby eliminating the severe oversupply of lubricant and resulting negative consequences to the environment and the quality of the pressing. In multi-stage tooling presses, lubricant very often does not reach critical parts of the product or tooling i.e. lubricant starvation occurs, again causing reduced tool life and/or unacceptable quality of pressings. The remotely placed gun, offers a solution when the press opens for short time duration. In general, stainless tube cutting has benefited significantly by using MQL, cutting down cost in tooling and lubricant usage.

The problem of high temperatures in the cutting zone, as with steel, again limits the application of the MQL technique. However we are encouraged by the work of Autret et al. [32] who evaluated MQL vs. flood cooling in working of hardened bearing grade steel showing the technical feasibility of MQL. This was confirmed by Beno et al. [33–36], who have shown that it is possible to work difficult-to-machine metals such as Ti-6Al4 V, Waspalloy, Inconel 718 and Greek Ascaloy, using the MQL technique.

20.4.5 The Future

As local legislation pertaining to the *environment* and in particular to protect our scarce water resources, becomes more stringent, more attention must be given to how we can widen the scope of MQL application. Two areas are being investigated:

- First, we are studying the concurrent application of minute drops of water with the lubricant to use the latent heat of evaporation to bring down the temperature of the steel/stainless steel metal removal/forming operation, without ending up with a wet production environment. The work by Wang et al. [37] and Joubert [38] give good indications that this approach can be applied in practice.
- Second, we must continue our search for better lubricants without sacrificing our commitment to the environment. In this regard, the use of nano-sized solid particles dispensed in the plant oil [39] is an area of hope in our potential quest for a cleaner and sustainable environment.

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